

A heavier gluino from t - b - τ Yukawa-unified SUSY

Howard Baer^{a,1}, Shabbar Raza^{b,2} and Qaisar Shafi^{b,3}

^a *Dep't of Physics and Astronomy, University of Oklahoma,
Norman, OK 73019, USA*

^b *Bartol Research Institute, Department of Physics and Astronomy,
University of Delaware, Newark, DE 19716, USA*

Abstract

Supersymmetric models with t - b - τ Yukawa coupling unification and unified gaugino masses at the GUT scale– with $\mu > 0$ – show a mild preference for light gluino masses $m_{\tilde{g}} \lesssim 500$ GeV. This range of $m_{\tilde{g}}$ is now essentially ruled out by LHC searches. We show that a heavier gluino with $m_{\tilde{g}} \sim 0.5$ – 3 TeV can also be compatible with excellent t - b - τ Yukawa coupling unification in supersymmetric models with non-universal Higgs masses (NUHM2). The gluino in such models is the lightest colored sparticle, while the squark sector displays an inverted mass hierarchy with $m_{\tilde{q}} \sim 5$ – 20 TeV. We present some LHC testable benchmark points for which the lightest Higgs boson mass $m_h \simeq 125$ GeV. We also discuss LHC signatures of Yukawa-unified models with heavier gluinos. We expect gluino pair production followed by decay to final states containing four b -jets plus four W -bosons plus missing E_T to occur at possibly observable rates at LHC.

¹ Email: baer@nhn.ou.edu

² Email: shabbar@udel.edu. On study leave from: Department of Physics, FUUAST, Islamabad, Pakistan.

³ Email: shafi@bartol.udel.edu.

1 Introduction

Unification at M_{GUT} ($\sim 2 \times 10^{16}$ GeV) of $t - b - \tau$ Yukawa couplings[1, 2] is largely inspired by the simplest supersymmetric (SUSY) $SO(10)$ or $SU(4)_c \times SU(2)_L \times SU(2)_R$ models[3]. It has become clear in recent years[4, 5, 6, 7, 8, 9, 10, 11] that imposing $t - b - \tau$ Yukawa coupling unification has important consequences for the sparticle and higgs mass spectrum of the minimal supersymmetric standard model (MSSM). The successful launch of the Large Hadron Collider (LHC) has provided important new impetus for these studies[12, 13, 14]. For analogous discussion of $b - \tau$ unification, see Ref. [15].

The parameter space of $SO(10)$ SUSY GUT models for this investigation is given by

$$m_{16}, m_{H_u}^2, m_{H_d}^2, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu), \quad (1)$$

where m_{16} is the unified matter scalar mass, $m_{H_u}^2$ and $m_{H_d}^2$ are the GUT scale Higgs soft masses, $m_{1/2}$ is the unified gaugino mass, A_0 is the coefficient of the soft supersymmetry breaking (SSB) trilinear term, and $\tan \beta$ is the ratio of Higgs field vevs. In order to allow for an appropriate radiative breaking of electroweak symmetry, the two GUT scale Higgs doublet masses must be split[16] according to $m_{H_u}^2 < m_{H_d}^2$. This splitting might arise due to $SO(10)$ D -terms (D -term splitting) or via GUT-scale threshold corrections[7] (the Higgs splitting, or HS model). With the MSSM superpotential parameter $\mu > 0$, this scenario predicts an inverted scalar mass hierarchy (IMH)[17] in the squark sector, wherein third generation squarks have masses in the few TeV range, while the first two generations of squarks have mass in the 5-30 TeV range[6]. The IMH allows one to reconcile a decoupling solution to the SUSY flavor and CP problems with relatively low fine-tuning in the EWSB sector. A successful implementation of the IMH scheme requires GUT-scale SSB terms to be related as $A_0^2 \simeq 2m_{10}^2 \simeq 4m_{16}^2$, with unified third generation Yukawa couplings and the unified gaugino mass $m_{1/2}$ on the low side: typically sub-TeV.

One particularly important prediction concerns the gluino which turns out to be the lightest colored SUSY particle.¹ Since $m_{1/2}$ is favored to be small in comparison to m_{16} , there is some tendency in $t - b - \tau$ unified models for $m_{\tilde{g}} \lesssim 500$ GeV, which should be within range of SUSY searches at LHC operating with $\sqrt{s} = 7$ TeV (LHC7)[20]. In this case, due to the large b -quark Yukawa coupling and the inverted squark mass spectrum, gluinos are expected to dominantly decay by 3-body

¹These predictions are obtained under the assumption that the lightest neutralino is the lightest MSSM particle (LMP). This class of Yukawa-unified models tends to predict a thermal neutralino relic abundance $\Omega_{LMP} h^2 \gg 1$ so that the neutralino LMP in this scenario is not a viable dark matter candidate. To overcome this drawback, one proposal[18, 19] is to invoke axion physics and arrange for the lightest neutralino to decay before nucleosynthesis into an axino, which now plays the role of lightest SUSY particle (LSP). A combination of axions and axinos could then make up the dark matter content of the universe.

modes such as $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_i^0$, leading to final states at LHC consisting of multiple b -jets + MET [12, 13].

In fact, recent searches by the ATLAS experiment with less than 1 fb^{-1} of data already exclude $m_{\tilde{g}} \lesssim 500 \text{ GeV}$ by searching for multijet plus missing E_T (MET) plus one or more tagged b -jets[14]. Also, direct searches for gluinos and squarks under the assumption of unified gaugino masses by Atlas and CMS (again with $\sim 1 \text{ fb}^{-1}$ of data) typically exclude $m_{\tilde{g}} < 550 - 750 \text{ GeV}$ (depending on search techniques)[21, 22]. Based on this critical input from experiment, the question arises: Are $t - b - \tau$ unified models now excluded by LHC searches, or can Yukawa-unified solution be found with heavier gluinos with mass beyond current LHC reach? And if such solutions are found, what is the nature of the SUSY signal which is expected in near future runs of LHC7?

Our main goal in this paper is to determine whether Yukawa-unified solutions with a heavier gluino can exist. In fact, we find numerous solutions, some of which are presented as a new set of benchmark points with $m_{\tilde{g}}$ in the range $0.5 - 3 \text{ TeV}$. In these solutions, the gluino retains its position as the lightest colored SUSY particle, while squarks remain in the multi-TeV range. Thus, we expect in this class of models that LHC searches should focus on gluino pair production. However, for these heavier gluino solutions, the \tilde{g} is expected to decay via $\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_1^\pm$ or $t\bar{t}\tilde{\chi}_i^0$. After $t \rightarrow bW$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W$ decays, we expect gluino pair production final states to contain typically four b -jets, four W bosons plus MET. These are in rather sharp contrast with models containing $m_{\tilde{g}} \lesssim 500 \text{ GeV}$, where multi- b -jets+ MET final states are expected, but without the numerous on-shell W bosons.

Note that due to potential threshold corrections which could arise from a variety of sources including a more complicated Higgs sector, higher order interaction terms, etc., we do not insist on exact (or perfect) unification of the three Yukawa couplings. Instead, in this paper Yukawa unification realized at the 10% level (or better) is considered to yield an acceptable scenario. In practice, we find solutions with heavy ($\sim 2 - 3 \text{ TeV}$) gluino masses that are associated with Yukawa unification at a few percent level. Somewhat lighter gluino masses ($\sim 1 - 1.5 \text{ TeV}$) are accompanied by essentially perfect Yukawa unification! As expected, the squark masses display an inverted mass hierarchy, with the lightest (third family) squark masses ranging between 1 to 10 TeV. The first two family squarks turn out to be considerably heavier, of order 8-28 TeV. In the benchmark points that we highlight in this paper, the mass of the SM-like Higgs boson is of order 124-126 GeV, a value which is consistent with results from recent ATLAS and CMS Higgs searches[23].

2 Phenomenological constraints and scanning procedure

We employ the ISAJET 7.80 [24] package Isasugra[25] to perform random scans over the fundamental parameter space. In this package, the weak scale values of gauge and third generation Yukawa couplings are evolved to M_G via the MSSM renormalization group equations (RGEs) in the \overline{DR} regularization scheme. We do not strictly enforce the unification condition $g_3 = g_1 = g_2$ at M_G , since a few percent deviation from unification can be assigned to unknown GUT-scale threshold corrections [26]. The deviation between $g_1 = g_2$ and g_3 at M_G is no worse than 3 – 4%. For simplicity we do not include the Dirac neutrino Yukawa coupling in the RGEs, whose contribution is usually small[27].

The various HS model boundary conditions are imposed at M_G and all the SSB parameters, along with the gauge and Yukawa couplings, are evolved back to the weak scale M_Z . In the evaluation of Yukawa couplings, the SUSY threshold corrections [28] are taken into account at the common scale $M_{\text{SUSY}} = \sqrt{\bar{m}_{\tilde{t}_L} \bar{m}_{\tilde{t}_R}}$. The entire parameter set is iteratively run between M_Z and M_G using the full 2-loop RGEs until a stable solution is obtained. To better account for leading-log corrections, one-loop step-beta functions are adopted for gauge and Yukawa couplings, and the SSB parameters m_i are extracted from RGEs at multiple scales $m_i = m_i(m_i)$. The RGE-improved 1-loop effective potential is minimized at M_{SUSY} , which effectively accounts for the leading 2-loop corrections. Full 1-loop radiative corrections are incorporated for all sparticle masses.

The requirement of radiative electroweak symmetry breaking (REWSB) imposes an important theoretical constraint on the parameter space. In order to reconcile REWSB with Yukawa unification, the MSSM Higgs soft supersymmetry breaking (SSB) masses should be split in such way that $m_{H_d}^2/m_{H_u}^2 > 1.2$ at M_G [29]. As mentioned above, the MSSM doublets reside in the 10 dimensional representation of $SO(10)$ GUT for Yukawa unification condition to hold. In the gravity mediated supersymmetry breaking scenario[30], the required splitting in the Higgs sector can be generated by involving additional Higgs fields[10], or via D-term contributions[31]. In our Yukawa-unified SUSY spectrum calculations, the lightest neutralino is always turns out to be the LMP.

We have performed Markov-chain Monte Carlo (MCMC) scans for the following

parameter range:

$$\begin{aligned}
0 &\leq m_{16} \leq 30 \text{ TeV} \\
0 &\leq m_{H_u} \leq 35 \text{ TeV} \\
0 &\leq m_{H_d} \leq 35 \text{ TeV} \\
0 &\leq m_{1/2} \leq 5 \text{ TeV} \\
30 &\leq \tan \beta \leq 60 \\
-3 &\leq A_0/m_0 \leq 3
\end{aligned} \tag{2}$$

with $\mu > 0$ and $m_t = 173.3 \text{ GeV}$ [32]. Note that our results are not too sensitive to one or two sigma variation in the value of m_t [10]. We use $m_b^{\overline{DR}}(m_Z) = 2.83 \text{ GeV}$ which is hard-coded into ISAJET.

In scanning the parameter space, we employ the Metropolis-Hastings algorithm as described in [33]. The data points collected all satisfy the requirement of REWSB, with the neutralino in each case being the LMP. After collecting the data, we impose the mass bounds on all the particles [34] and use the IsaTools package [35, 36] and Ref. [37] to implement the various phenomenological constraints. We successively apply the following experimental constraints on the data that we acquire from Isasugra:

$$\begin{aligned}
m_h \text{ (lightest Higgs mass)} &\geq 114.4 \text{ GeV} & [38] \\
BR(B_s \rightarrow \mu^+ \mu^-) &< 1.1 \times 10^{-8} & [39] \\
2.85 \times 10^{-4} \leq BR(b \rightarrow s \gamma) &\leq 4.24 \times 10^{-4} \text{ (} 2\sigma \text{)} & [40] \\
0.15 \leq \frac{BR(B_u \rightarrow \tau \nu_\tau)_{\text{MSSM}}}{BR(B_u \rightarrow \tau \nu_\tau)_{\text{SM}}} &\leq 2.41 \text{ (} 3\sigma \text{)} & [41]
\end{aligned}$$

As far as the muon anomalous magnetic moment a_μ is concerned, we require that the benchmark points are at least as consistent with the data as the Standard Model is. For a presentation of $(g - 2)_\mu$ values in NUHM2 models, see [42].

3 A heavier gluino from Yukawa-unified SUSY

In order to quantify Yukawa coupling unification, we define the quantity $R_{tb\tau}$ as

$$R_{tb\tau} = \frac{\max(y_t, y_b, y_\tau)}{\min(y_t, y_b, y_\tau)}. \tag{3}$$

In Fig. 1 we plot $R_{tb\tau}$ versus the various $SO(10)$ model input parameters. Gray points are consistent with REWSB and neutralino LSP. Orange points satisfy the mass bounds (including m_h in the range 115–131 GeV and $m_{\tilde{g}} \geq 0.5 \text{ TeV}$), constraints from $BR(B_s \rightarrow \mu^+ \mu^-)$, $BR(B_u \rightarrow \tau \nu_\tau)$ and $BR(b \rightarrow s \gamma)$. Blue point solutions belong to a subset of orange points and represent m_h in the range 123 – 127 GeV. In Fig.

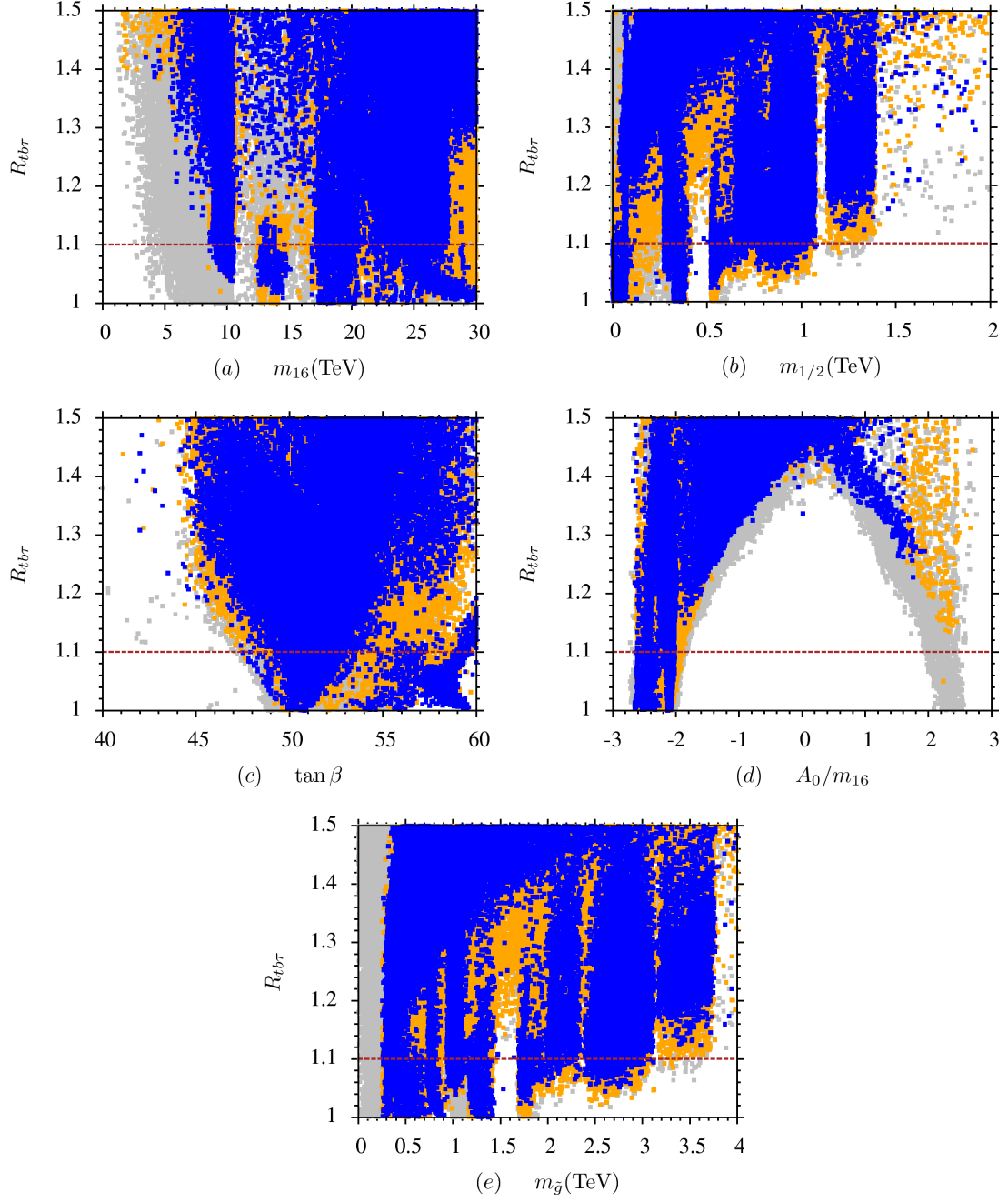


Figure 1: Plots in $m_{16} - R_{tb\tau}$, $m_{1/2} - R_{tb\tau}$, $\tan \beta - R_{tb\tau}$, $A_0/m_{16} - R_{tb\tau}$, and $m_{\tilde{g}} - R_{tb\tau}$ planes. Gray points are consistent with REWSB and neutralino LSP. Orange points satisfy mass bounds (including m_h in the range 115 – 131 GeV and $m_{\tilde{g}} \geq 0.5 \text{ TeV}$), constraints from $BR(B_s \rightarrow \mu^+ \mu^-)$, $BR(B_u \rightarrow \tau \nu_\tau)$ and $BR(b \rightarrow s \gamma)$. Blue point solutions belong to a subset of orange points and represent m_h in the range 123 – 127 GeV.

1a), we see, as is well known, that $m_{16} \gtrsim 10$ TeV for solutions with $R_{tb\tau} < 1.1$, as required by the inverted scalar mass hierarchy. In Fig. 1b), we also see that low values of $m_{1/2}$ are favored. While previous works favored $m_{1/2} \lesssim 0.1 - 0.2$ TeV, here our dedicated MCMC scans show $t - b - \tau$ unified solutions can also occur for $m_{1/2}$ values in the $0.3 - 1$ TeV range. Fig. 1c) shows that $\tan\beta \sim 50 - 60$ is required, while Fig. 1d) shows that $A_0 \sim -2m_{16}$ is required for the IMH. Our key result here occurs in Fig. 1e), where we plot the value of $m_{\tilde{g}}$ *vs.* $R_{tb\tau}$. Here, we find that while many solutions occur with $m_{\tilde{g}} \lesssim 0.5$ TeV, there also exist solutions with near perfect Yukawa unification with substantially heavier gluino masses ranging up to $m_{\tilde{g}} \sim 1.4$ TeV. And if we only require $R_{tb\tau} \lesssim 1.1$, then some solutions can occur with $m_{\tilde{g}}$ as large as 3 TeV!

4 Heavier gluino benchmark points and implications for SUSY searches at LHC

In Table 1, we list four benchmark (BM) Yukawa-unified solutions from Isajet 7.80 with $m_{\tilde{g}} > 500$ GeV. Each BM point also has $m_h = 125 \pm 2$ GeV, so all are consistent with the Atlas/CMS hint of a Higgs signal around 125 GeV.

For point 1, with $m_{16} \simeq 21$ TeV, all the squarks and sleptons are far beyond the reach of LHC. However, for this point, $m_{\tilde{g}} = 750$ GeV, and so gluinos would be pair-produced at LHC7 with a cross section of ~ 60 fb[12]. In Ref. [12], LHC search strategies assumed a much lighter gluino of mass $\sim 0.3 - 0.6$ TeV, in which case gluino three body decays to $b\bar{b}\tilde{\chi}_i^0$ are dominant, and the search strategy was to look for collider events containing multiple b -jets + MET . For point 1, at the bottom of the Table we list the dominant gluino branching fractions. In this case, with $m_{\tilde{g}} \sim 750$ GeV, the decay modes $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_i^0$ and $\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_j^-$ occur at substantial rates: in this case $\sim 60\%$. Here, $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 W$ at 100% branching fraction, while $t \rightarrow bW$ also at 100%. Thus, gluino pair production for Yukawa-unified benchmarks and a heavier gluino lead to final states including four b -jets, four on-shell W -bosons + MET . Since the W s decay into hard isolated leptons over 20% of the time, these gluino pair production events will contain *high multiplicities of isolated leptons*, including same sign (SS) and opposite-sign (OS) pairs, trileptons and four-leptons! There are few SM background (BG) processes that can lead to events containing for instance four b -jets plus four isolated leptons. The major BG process would likely be four top production: $pp \rightarrow t\bar{t}t\bar{t}X$.

In addition, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production can occur at large rates for the Yukawa-unified BM points[12]. For all cases listed, $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W$ at $\sim 100\%$ branching fraction, and $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ with typically a branching fraction $\gtrsim 90\%$. Recently, it has been pointed out[43] that the process $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow Wh\tilde{\chi}_1^0 \tilde{\chi}_1^0$ should be visible at LHC with

	Point 1	Point 2	Point 3	Point 4
m_{16}	21370	20230	18640	26130
$m_{1/2}$	93.41	364	579	1021
A_0/m_{16}	-2.43	-2.13	-2.09	-2.11
$\tan \beta$	57.2	51	50	52
m_{H_d}	22500.0	26770	24430	34210
m_{H_u}	13310.0	23260	21780	30590
m_h	126.7	125	124	124
m_H	9389	3192	3145	4066
m_A	9328	3171	3125	4040
m_{H^\pm}	9390	3193	3147	4067
$m_{\tilde{g}}$	750	1375	1853	2991
$m_{\tilde{\chi}_{1,2}^0}$	122, 285	232, 491	323,661	557,1114
$m_{\tilde{\chi}_{3,4}^0}$	19295, 19295	6048,6048	4570,4571	6315,6315
$m_{\tilde{\chi}_{1,2}^\pm}$	286, 19330	493,6021	664,4542	1118,6275
$m_{\tilde{u}_{L,R}}$	21389,21132	20230,20115	18653,18574	26187,26079
$m_{\tilde{t}_{1,2}}$	7389,8175	3465,5356	3089,5447	4376,7901
$m_{\tilde{d}_{L,R}}$	21389,21513	20230,20333	18653,18742	26187,26304
$m_{\tilde{b}_{1,2}}$	7836,8234	5417,6047	5534,6584	8038,9652
$m_{\tilde{\nu}_1}$	21196	20128	18565	26037
$m_{\tilde{\nu}_3}$	15502	15066	14032	19441
$m_{\tilde{e}_{L,R}}$	21193,21717	20123,20416	18559,18779	26027,26319
$m_{\tilde{\tau}_{1,2}}$	7490,15463	8048,15079	7796,14042	9984,19455
$\Omega_{CDM} h^2$	12642	190	972	1377
$R_{tb\tau}$	1.06	1.00	1.05	1.07
$BF(\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_i^0)$	0.33	0.13	0.07	0.06
$BF(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_i^0)$	0.15	0.15	0.69	0.75
$BF(\tilde{g} \rightarrow t\bar{b}\tilde{\chi}_j^- + c.c.)$	0.45	0.33	0.22	0.18

Table 1: Sparticle and Higgs masses (in GeV). All of these benchmark points satisfy the various constraints mentioned in Section 2 and are compatible with Yukawa unification. Point 1 exhibits a solution near the current reach limit of LHC. Point 2 exhibits ‘perfect’ Yukawa unification. Point 3 displays an example of a relatively heavy gluino within reach of LHC14. Point 4 represents a solution with the heaviest gluino (~ 3 TeV) we have in our scans; it is likely beyond reach of LHC. The uncertainty in the Higgs mass (m_h) estimates is about ± 2 GeV.

$\sqrt{s} = 14$ TeV and $\sim 100 - 1000 \text{ fb}^{-1}$ of integrated luminosity. This latter gaugino pair production signal offers a second corroborative channel for claiming a SUSY discovery

in models with lighter gauginos and decoupled squarks and sleptons. In addition, in the Wh channel, the $p_T(h)$ distribution may allow a chargino/neutralino mass extraction provided a very large data sample is acquired. Likewise, for $m_{\tilde{g}} \sim 500\text{--}800$ GeV, then $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$. In this case, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production will yield $WZ + MET$ events, for which the $WZ \rightarrow 3\ell$ and possibly $WZ \rightarrow \ell^+ \ell^- + jets$ signatures may be visible at LHC7[44].

For point 2 in Table 1, we show a case with essentially perfect Yukawa unification, $R_{tb\tau} = 1.0$, but with $m_{\tilde{g}} = 1375$ GeV. In this case, the combined branching fraction for gluinos into top quark final states has increased to $\sim 86\%$. With such a heavy gluino, this case would likely be beyond the reach of LHC7[20]. However, it should be within reach of LHC with $\sqrt{s} = 14$ TeV (LHC14), which should start operating around 2015. Benchmark point 3 in Table 1 shows a case with $m_{\tilde{g}} = 1853$ GeV and decoupled scalars. This case, with such a heavy gluino mass, lies right around the ultimate reach of LHC14 with 100 fb^{-1} , in a search for gluino pair production. However, the Wh search channel from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production may be competitive with gluino pair searches in this case assuming $100\text{--}1000\text{ fb}^{-1}$ of integrated luminosity.

The last point 4 in Table 1 corresponds to $R_{tb\tau} = 1.07$, but with $m_{\tilde{g}} = 2991$ GeV and decoupled scalars. This is the case with the largest gluino mass we were able to find while requiring $R_{tb\tau} < 1.1$ and $m_h \sim 125$ GeV. This case would likely lie beyond reach of LHC14 for any luminosity upgrade. Detection of a SUSY signal in this case would likely require a pp collider with $\sqrt{s} \sim 40\text{--}100$ TeV.

5 Conclusion

Previous papers examining $t - b - \tau$ Yukawa-unified models with gaugino mass unification and $\mu > 0$ have focused on solutions with rather light gluinos: $m_{\tilde{g}} \lesssim 0.5$ TeV. These models are now likely all excluded by recent or soon-to-be-released LHC SUSY searches. In light of these earlier results, we were motivated to examine if Yukawa-unified solutions with heavier gluinos could exist, while also requiring $m_h \sim 125$ GeV, as is recently hinted at by Atlas and CMS. Using dedicated MCMC scans over $SO(10)$ parameter space, we have found solutions with excellent Yukawa unification and $m_{\tilde{g}}$ ranging up to 1.4 TeV, well beyond current LHC search limits. Loosening the Yukawa-unification criteria to $R_{tb\tau} < 1.1$, we even find solutions with $m_{\tilde{g}}$ nearly 3 TeV.

We have listed four $SO(10)$ benchmark points with $m_{\tilde{g}}$ spanning the range $0.75\text{--}2.9$ TeV. Regarding LHC SUSY searches, we note that these heavier gluino solutions will be characterized by gluino pair production at LHC, followed by decays to final states including four b -jets, four on-shell W bosons $+MET$. The gluino pair events should be rich in multiple isolated leptons plus b -jets, and the dominant SM background will likely arise from four top production.

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